

# Study and Development of an Energy Saving Mechanical System

Zheng (Jeremy) Li

University of Bridgeport/Department of ME, Bridgeport, CT 06604, USA

zhengli@bridgeport.edu

**Abstract:-** A new energy-saving mechanical system with automatically controlled air valves has been proposed by investigator and the preliminary model setup has been tested. The testing results indicated the proper function of this energy-saving mechanical system. This mechanical system model has been simulated and analyzed by the computational aided engineering solution. The major advantages of this mechanical system include: simple and compact in design, higher efficiency in mechanical functioning, quiet in manufacturing operation, less energy losses due to less frictional forces in this free piston-cylinder setup, self-adjustable in operational parameter to improve the system performance, and etc.

**Keywords:-** Energy saving, Computational modeling, System optimization, Finite element analysis

## I. NOMENCLATURE

$V_c (V'_c)$  - volumes of right and left compressive cylinders  
 $V_e (V'_e)$  - volume of right and left expansive cylinders  
 $F (F')$  - free pistons in right and left expansive cylinders  
 $V_{mc} (V'_{mc})$  - middle fluctuation cavities in right and left expansive cylinders  
 $P_h$  - high pressure  
 $P_l$  - low pressure  
 $A_g$  - cross section area of working gap  
 $r$  - positive constant characteristic of the system with the units of 1/time, and is sometimes expressed in terms of a time constant  $r = 1/t_0$   
 $T(t)$  - temperature at the time  $t$   
 $T(0)$  - initial temperature at zero time, or  $t = 0$   
 $\Delta T(0)$  - initial temperature difference at time 0  
 $V_k$  - volume of clearance  
 $H$  - compressive piston  
 $A, \beta$  - crank turning angle at different time  
 $T_c, T_e, T_k$  - temperatures in compressive chamber, expansive chambers and clearance cavity,  
 $R$  - gas constant  
 $M_i$  - mass in expansive chamber, compressive chamber and clearance cavity with  $i$  indicating the index of compressive, expansive and clearance volumes  
 $M_t$  - total gas mass in this energy-saving system.  
 $Y_e$  - moving distance of free piston  
 $Y_o$  - maximum moving distance of free piston  
 $m$  - mass of free piston  
 $w$  - turning angle speed of crank

## II. INTRODUCTION

The energy-saving mechanical systems applied in refrigerating units have been studied in the past and different R&D research work has been done to improve its function and implement more energy-saving features ([1] and [2]). In this paper, the investigator proposes a new energy-saving mechanical system with automatically controlled air valves and the prototype has been verified through the computational modeling simulation and lab testing. The simplified prototype and its functioning cycle are indicated in Fig. 1 and 2. This new mechanism makes the mechanical system more simply and compact. The gas pressure can be self-adjusted by two automatic valves AV controlled by PLC program in the control unit and the free piston's travel is also controlled by two electric sensors ES to improve the system performance over different environmental conditions. In addition, partial compressive work within middle fluctuating cavity in this new system can be converted to the useful work compared with some mechanical/thermal systems such as Solvay system in which no energy can be retrieved from middle cavity where the total compressive work is exhausted to the air as the heat ([3] and [4]). Also the thermal efficiency of the mechanical system has been improved because the refrigerating energy capacity can be delivered through two ends of cylinder. The mechanical vibration has been significantly reduced due to its symmetrical balancing setup. The phase angle of its performance and functional curves can be self-adjusted with PLC program through the automatically controlled valves to improve the system performance and efficiency.

## III. SYSTEM PERFORMANCE

The system cycle can be analyzed based on Fig.1 and 2. Two air-controlled valves, two electric sensors, two compressive cylinders  $V_c (V'_c)$ , two expansive cylinders  $V_e (V'_e)$  are symmetrically installed in this system. In addition, two identical free pistons  $F (F')$ , one fixed plate  $G$  with a tiny hole on the middle of it and two middle fluctuation cavities  $V_{mc} (V'_{mc})$  are also indicated in the pictures. Due to its symmetrical configuration, only right side, namely  $V_c, V_e$  and  $V_{mc}$ , compressor piston  $H$  and free piston  $F$  required to be studied and analyzed. The initial condition of this mechanical system is indicated in Fig.1 with its steady working condition being reached at its first stage of the cycle, piston  $H$  being at the bottom position in the compressive chamber and free piston  $F$  being at the right end of expansive chamber. Since

the gaseous media with high pressure ( $P=P_h$ ) flows into  $V_{mc}$  through a tiny hole at the end period of last functioning cycle, gaseous media with low pressure ( $P=P_l$ ) in  $V_{mc}$  gas has been mixed with high-pressure gaseous media. The mixed pressure in  $V_{mc}$  is  $P_{wa}$ . While  $H$  starts to move upward in  $V_c$ , gaseous media in  $V_{mc}$  is assumed not flowing into  $V'_{mc}$  since the moving speed of the piston is so fast and the diameter of hole is so tiny. Because the gaseous pressure in left side of  $F$  is higher than the right side of  $F$  ( $P_{mc} = P_{wa} > P_c$ ),  $F$  is not moving and  $P_c$  is reaching to  $P_h$  and  $V_c$  is increasing from zero to  $V_2$  as  $H$  is continuously moving up. This process is indicated as curve 1-2 in Fig.3 and then gaseous media in  $V_{mc}$  enters  $V'_{mc}$ . In this period, pressure at the left and right sides of  $F$  is same and  $F$  moves to the left with constant speed. When crank angle  $\alpha$  reaches  $180^\circ$ ,  $V_c$  increases from  $V_2$  to  $V_3$  and this process is shown as line 2-3. In the earlier stage that  $H$  moves downwards in  $V_c$ ,  $F$  does not move since the gaseous media in  $V'_{mc}$  is assumed not entering  $V_{mc}$ .  $P_c$  reduces from  $P_3$  to  $P_4$  with corresponding course 3-1. As  $H$  is continuously moving downwards in  $V_c$ , gaseous media in  $V'_{mc}$  is flowing into  $V_{mc}$  through tiny hole and  $F$  is moving to the right end in the expansive chamber in constant speed and corresponding process is 4-1. This concludes the full functioning cycle including all the above processes. With the addition of two automatically controlled valves, the gaseous pressure in  $V_{mc}$  and  $V'_{mc}$  can be self-adjusted to change the phase angles of all performance curves to improve the mechanical and thermal functions of the system through PLC controlled automatic valves. Two electric sensors at two ends of the expansive chambers can monitor the motion of free pistons that can be fed back to the PLC unit to readjust the mechanical and thermal parameters to optimize the system function.

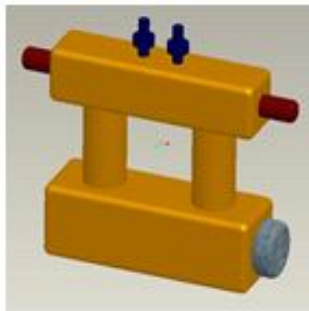


Figure 1. Prototype

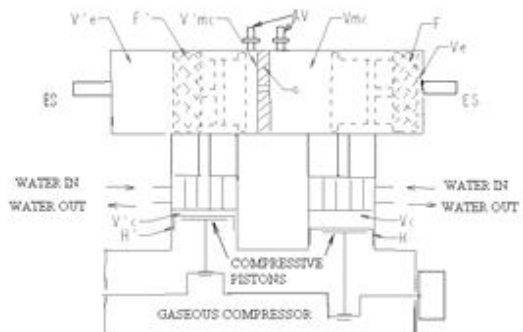


Figure 2. Simplified Energy-Saving Mechanism

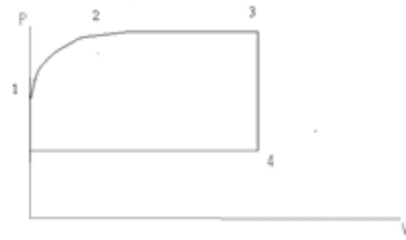


Figure 3. P-V Diagram of System Cycle in Expansive Chamber

#### IV. COMPUTATIONAL MODELING

This new mechanical prototype has been tested and the experimental results indicated that this new energy-saving system is feasible in function and performance. The computational modeling and analytic simulations have been performed to study and verify the functionality of this automatically controlled mechanical system and all functional parameters can be determined as follows. If  $T(t)$  is the temperature of expansive chamber at time  $t$ , and  $T_{env}$  is the environmental temperature around this mechanical system, then

$$\frac{dT(t)}{dt} = -r(T - T_{env}) \quad (1)$$

The solution of this differential equation can be determined by integration and substitution of boundary conditions:

$$T(t) = T_{env} + [T(0) - T_{env}] e^{-rt} \quad (2)$$

If:

$$\Delta T(t) \text{ is defined as } T(t) - T_{env} \quad (3)$$

then the Newtonian solution is written as:

$$\Delta T(t) = \Delta T(0) e^{-rt} \quad (4)$$

Because the piston  $H$  in compressive chamber moves in sine law, we can get

$$V_c(\alpha) = \frac{1}{2} * N * V_{co} * [1 + \cos(\alpha)] \quad (5)$$

If  $V_k$  is the volume of clearance, then

$$V = V_k + V_c + V_e \quad (6)$$

$$P = R * \sum M_i * \left[ \frac{T_k}{V_k} + \frac{T_e}{V_e} + \frac{T_c}{V_c} \right] \quad (7)$$

When compressive piston  $H$  moves up with crank turning to some angle  $\beta$ ,

$$(P_e - P_{me}) * S = F_f \quad (8)$$

$$P() = R * M_i * [] \quad (9)$$

Assume:

$$W = , L = , Q = ,$$

Combine (3) and (5):

$$P = P(\beta) * \left\{ \frac{L * W + \frac{V_c(\beta)}{V_{eo}}}{L * W + \frac{V_e}{V_{eo}} * Q + \frac{V_c(\beta)}{V_{eo}}} \right\} \quad (10)$$

From equation (10), the solution of  $P = P(\alpha)$  can be determined after relation between  $V_e$  and  $\alpha$  being found. The differential

equation of motion for free piston can be indicated, based on Newton's second law, as follows:

$$m \cdot (d^2 Y_c / dt^2) = P_c - P_{mc} \cdot S - F_f \quad (11)$$

Combine equations (10) and (11):

$$\frac{d^2 \left[ \frac{V_e(\alpha)}{V_{eo}} \right]}{d\alpha^2} = P(\beta) \cdot [L \cdot W + \frac{V_c(\beta)}{V_{eo}} \cdot m \cdot W^2 \cdot \frac{Y_o}{S} \cdot (L \cdot W + Q \cdot \frac{V_e(\alpha)}{V_{eo}} + \frac{V_c(\alpha)}{V_{eo}} - 2 \cdot V_{eo} \cdot S \cdot (P_l + P_h) \cdot m \cdot W \cdot Y_o)] \quad (12)$$

So  $P(\beta)$  can be calculated by the following equation:

$$\frac{d^2 V_c(\alpha)}{d\alpha^2} = 0 \quad (13)$$

Also,  $V_c(\alpha)$  can be determined by formula (9).

Based on the computer modeling and numerical analysis,  $V_c(\alpha)$  in (12) and  $P(\alpha)$  in (10) can be determined. Through the computational simulation and solutions, the relations among all functional parameters can be shown in Figs.4, 5, 6, 7 and 8, which indicate the proper and feasible function of this automatically controlled energy-saving mechanical system.

The results show that the refrigerating temperature can reach to 152°K and the output refrigerating capacity is 388 Btu/hr with media gas of nitrogen and crank turning speed of 150 r/min. The refrigerating temperature over time is indicated in Fig.4, the relation that  $P/P_{max}$  changes with  $\alpha$  is shown in Fig.5, the indicator cards in expansive chamber and full system are presented in Fig.6 and 7, and the distributions of mass ( $M_e$  in expansive chamber,  $M_c$  in compressive chamber and  $M_k$  in clearance cavity) are found in Fig.8. All these diagrams indicated that this automatically controlled energy-saving mechanical system functions properly because all parameter performance curves of pressure and mass in this machinery system are feasible and acceptable. The above computational solution also closely matches the testing results from prototype.

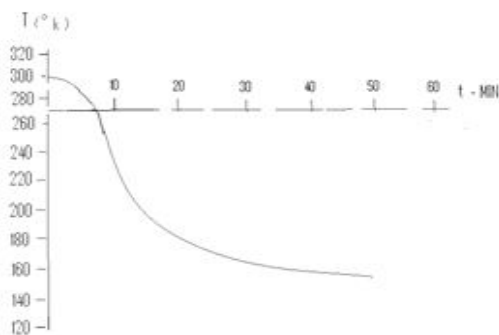


Figure 4. Refrigerating Temperature over Time

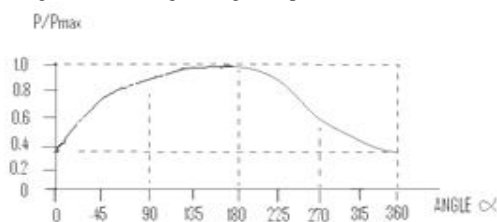


Figure 5. Pressure Ratio  $P/P_{max}$  over Crank Angle  $\alpha$

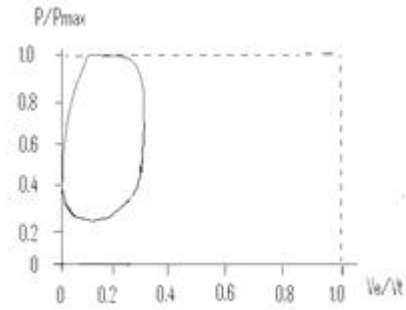


Figure 6. Pressure Ratio  $P/P_{max}$  over Volume Ratio  $V_e/V_i$  in Expansive Chamber

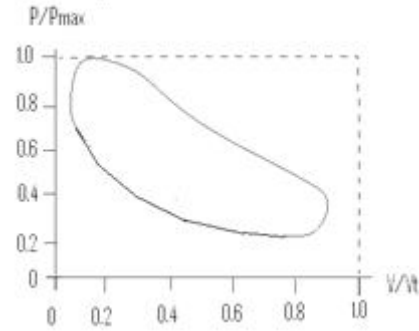


Figure 7. Pressure Ratio  $P/P_{max}$  over Volume Ratio  $V/V_i$  in Total Chamber

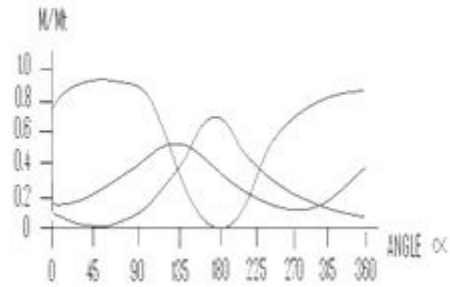


Figure 8. Mass Ratio  $M_i/M_t$  over Crank Angle  $\alpha$  in Compressive, Expansive Chambers and Clearance Cavity

## V. CONCLUSION

The feasible functioning of this automatically controlled energy-saving mechanical system has been verified through the thermodynamic study, theoretical mechanism analysis, computational modeling simulation, and prototype testing. The major advantages of this system are that its performance can be easily controlled and optimized by adjusting the automatically controlled valves and monitoring of free piston's movement through the electric sensors, system is simple and compact, vibration is significantly reduced due to its symmetrical structure, performance efficiency is improved because its refrigerating capacity can be carried out through both ends of the cylinder.

## REFERENCES

- [1] J. Liu and A. D. Rosato, "Migration of An Intruder in a Boundary Driven Granular Flow", *Journal of Physics: Condensed Matter* 17, S2609-S2622, (2005).
- [2] Bao Yang & Zenghu Han, "A New Type Of Nanoengineered Heat Transfer Fluids: Nanoemulsion Fluids", 2006 ASME International Mechanical Engineering Congress and Exposition, Chicago, IL, USA, November 2006.
- [3] N. Zhang and A. D. Rosato, "Analysis of Instantaneous Dynamic States of Vibrated Granular Materials", *Mechanics Research Communications* 31 [5], 525-544, (2004).
- [4] W. Y. Lai, B. Ducelescu and P.E.Phelan, "Convective Heat Transfer With Nanofluids in a Single 1.02-mm Tube", 2006 ASME International Mechanical Engineering Congress and Exposition, Chicago, IL, USA, November 2006.